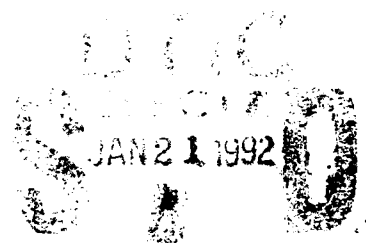AD-A244 532

Technical Report 1469
November 1991

Spatial Smoothing of Ionospheric Parameters for Use in the High-Frequency Benchmark Propagation Analysis Program
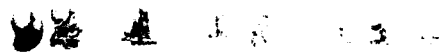
J. A. Ferguson
C. H. Shellman

JAN 2 1 1992

92-01627

NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152–5000

J. D. FONTANA, CAPT, USN
Commander

R. T. SHEARER, Acting
Technical Director

ADMINISTRATIVE INFORMATION

LH

CONTENTS

i

SUMMARY

OBJECTIVE

Develop a spatial smoothing routine that accepts arbitrary ionospheric models as input. Incorporate the smoothing routine into a sophisticated ray tracing model and state-of-the-art ionospheric model.

RESULTS

An extension of a smoothing algorithm previously developed by A. K. Paul of the Naval Ocean Systems Center was developed. A ray tracing model developed by R. M. Jones and J. J. Stephenson was implemented. The Utah State University Ionospheric Model, a parameterized version obtained from D. Anderson, was implemented.

CONCLUSIONS AND RECOMMENDATIONS

The iteration process required to obtain the coefficients for the interpolation uses too much computer time; a faster method is desirable. The ionospheric model needs to be changed to give more realistic electron densities in the lower altitudes; this will be very important if the model is to properly account for absorption. The ray trace model has some difficulty with the radical changes introduced by the ionospheric model; refinement of some of its procedures will be necessary.

INTRODUCTION

The Naval Ocean Systems Center (NOSC) is developing the High-Frequency Benchmark Propagation Analysis Program, or HF Benchmark. This program employs a sophisticated ray tracing program coupled with a state-of-the-art ionospheric model. The merging of these two major components depends critically on the development of a spatial smoothing routine that accepts arbitrary ionospheric models as input. Such a spatial smoothing routine has been developed by Paul (1991). This report describes a computer program that incorporates an extension of this smoothing algorithm together with the Jones and Stephenson (1975) ray tracing routine and the High Latitude Ionospheric Specification Model (HLISM).*

Ionospheric sounders have been used to probe the ionosphere for more than 40 years. Models of high-frequency (HF) propagation are based on the data acquired by these instruments. But, the ionosphere is highly variable. Lacking detailed understanding of the causes of ionospheric variations in the past, and being limited by lack of computing power, models of HF propagation have relied on synoptic data to develop global maps of key propagation parameters such as the maximum useable frequency (MUF). One failing of this approach is that large errors in prediction of critical propagation parameters occur under many important conditions. This is especially true at high latitudes. In part, errors in the models may be attributed to the fact that they are based almost exclusively on hourly averages taken at mostly middle latitude stations. Another important contribution to errors is the lack of reliable models of intermittent phenomena such as sporadic-E. Recent studies of data measured with a very high time resolution show that short-term fluctuations of the ionosphere may be large and that tilts in the ionosphere occur often (Paul, 1985).

The most widely used HF prediction codes in use today, PROPHET (Sailors, 1990) and IONCAP (Teters et al., 1983), are largely empirical, based on semiempirical models of ionospheric propagation. These programs have no provision for first principles, physics-based calculations. In the past, first principles codes were too slow, complex, and user-unfriendly to address the general class of problems that PROPHET and IONCAP attempted to address. Today, modern desktop computers rival the mainframes of the past, and the prospect of using modern first principles codes in routine propagation problem solving is a reality. Future HF prediction models will be hybrids consisting of rigorous physics-based propagation, expert systems to monitor and interpret realtime geophysical and ionospheric sensors, and improved man-machine interfaces.

---

* Source: Private communication with D. Anderson.

The goal of the work described in this report is to develop techniques that permit evaluation of different propagation models. The resulting program is to be as sophisticated as possible with concerns for computer run time to be subordinate to the use of realistic models of the environment. Employed with new databases of high-latitude propagation measurements, this model will be used to evaluate and improve the faster-running models and point to deficiencies in the ionospheric models.

SPATIAL SMOOTHING

The first step in this effort was to develop a generalized spatial smoothing routine that will accept arbitrary ionospheric profiles. A candidate spatial smoothing algorithm was developed by Paul (1991). He demonstrated a general function that permitted fitting a set of irregularly spaced discrete data with satisfying results. Maps of foF2 over Europe were generated, and ray tracing in the subsequent model ionosphere was tested (using no magnetic field and a flat earth). This algorithm has been extended to use a three-dimensional array of ionospheric profiles of electron density with altitude distributed in a grid of latitude and longitude.

The basic procedure in this algorithm is to define an ionospheric parameter at a series of coordinates. Currently, we chose this parameter to be the logarithm of the electron density. A single data point is characterized by a function, f_i, where

$$f_i(x, y, z) = 1 + \frac{a_i}{1 + \left(\dfrac{x - x_i}{r_{xi}}\right)^2 + \left(\dfrac{y - y_i}{r_{yi}}\right)^2 + \left(\dfrac{z - z_i}{r_{zi}}\right)^2} , \qquad (1)$$

and the value at a point (x, y, z) due to all of the data points in the set is given by

$$p(x, y, z) = p_o + p_s \, \Pi f_i(x, y, z). \qquad (2)$$

The quantities r_{xi}, r_{yi}, and r_{zi} are called the control distances and basically determine the range of influence of individual data points. We have found that these control distances should be about 80 percent of the separation of the data points in each direction. The quantities p_o and p_s are scaling parameters. We use them to normalize f_i. This improves the convergence of the iterations used to find the values of the unknown coefficients, a_i.

Modifications to the original procedure were required to consistently achieve convergence of the coefficients. Given that there is no functional form to impose on the iterations, the following procedure is used. The minimum value of the electron density data

2

is determined (p_o) and subtracted from all of the values. These data are then normalized using the peak value of the offset data (p_s). Equation 2 is used to compute a value at each of the input locations. A correction term is defined equal to the difference between the computed and input values of the logarithm of the electron density at the input locations. If the largest of these correction terms is less than a specified amount, then the iterations are terminated. Otherwise, the coefficients are adjusted by some fraction, and the calculations are repeated. Currently, we are using a maximum difference between these calculations and the input data of 0.1, which amounts to 10 percent of the logarithm of the peak electron density and seems to give reasonable results in about 30 iterations. We have run the algorithm using 0.01 or 1 percent of the peak value of the logarithm. This took 120 iterations and produced no discernable difference in the ray paths.

The large number of data points required to give a reasonable representation of the ionospheric variation along a propagation path seems to require that the fraction used to adjust the coefficients be quite small (0.05 in the current configuration of the program). This small value prevents oscillatory behavior of the iterative corrections, but requires a lot of iterations. We have implemented two procedures that improve the efficiency of the iterations. After much experimentation, we found that the initial estimate for the a_i should be some fraction of the quantity $d_i - 1$. Currently we use 0.6 for this fraction. The time required to calculate equation 2 is reduced by defining a factor that controls the range of influence of each data point. It can be seen in equation 2 that this is useful because the influence of each input data value decreases as the square of the distance. Data points outside of the range of influence of an interpolated point are not included in the calculation. The improvement in computation time is achieved by eliminating the large number of floating-point divisions found in equation 2 and avoiding calculation of terms that will not contribute to the total. In the current program, this range of influence is six times each of the control distances. This procedure also reduces the time required to generate interpolated values.

Three subroutines are used to implement the interpolation. The routine named AKP_MODEL takes the initial path parameters and sets up the array of data points by calculating the locations of the ionospheric profiles. The routine AKP_COEFF finds the quantities, p_o and p_s, and performs the iterations to determine the coefficients, a_i. The routine AKP_XYTHPH does coordinate conversion between the magnetic dipole coordinate system used in the ray trace routines and the quasi-Cartesian coordinate system used in the interpolation routine. This routine also calculates the derivatives of the ionospheric parameters due to the spatial variation of the ionosphere. The equations for performing these calculations are summarized in appendix A.

IONOSPHERIC MODEL

The ionospheric model currently used in the program is the Utah State University (USU) ionospheric model, a parameterized version which we obtained from Anderson.[*] This model is called the High Latitude Ionospheric Specification Model (HLISM). We have developed a subroutine driver for the model called *USU_MODEL*. This routine is called by *AKP_MODEL* to generate ionospheric profiles at points 500 km apart along the propagation path (defined by the transmitter and the receiver) and at points 500 km away on either side of the path along a direction perpendicular to the propagation path.

We chose the HLISM because it is considered one of the best high-latitude models available. Unfortunately, it is a model for positive ion densities in the altitude range from 100 to 800 km. We invoke charge neutrality and set the electron density equal to the total ion density. This is valid only where the negative ions can be ignored. The model tends to generate (correctly) large ion densities at the bottom of the ionosphere that would normally be neutralized by the presence of negative ions as well as electrons at those altitudes. For the moment, we have made an adjustment to the model as follows. We calculate the electron density down to 160 km and then append a value of 10^3 at 100 km and 10^2 at 60 km to the bottom of the profile. Under nighttime conditions, these values may cause a slight kink in the electron density profile. The adjustment is required to provide a gradual entry into the ionosphere for the ray tracing routine. We found that the unrealistically high values of electron densities at the bottom of the ionosphere were causing numerical problems in the ray tracing. We plan to obtain and implement an electron density model either as a modification of the USU model or as a replacement for it.

RAY TRACING

We have implemented the Jones and Stephenson (1975) ray tracing model. This is a versatile program with full allowance for externally specified models of the electron density, collision frequency, and geomagnetic field. We have made every effort to retain this flexibility in our implementation. In particular, the input requirements are nearly identical to the original Jones and Stephenson version with our model being called out as "AKPMODEL" in the specification of the ionospheric model. The output from the original model is retained. We have added additional parameters for input. These are summarized in table 1.

---

[*] Private communication with D. Anderson, 1991.

Minor procedural modifications have been made to facilitate running this program on a PC, but the FORTRAN used in the program is not specific to that platform. In fact, an identical capability exists for a VAX.

Table 1. Ray trace inputs for AKP model.

100	9	This value used to signal that the a_i have already been computed.
111	1	Number of the month
112	31	Day of the month
113	1991	Year
114	1200	UT in HHMM format
115	100	10 cm flux
116	1	k_p
117	1	Sign of B_y; 1 for "+"; -1 for "-"
118	160	Minimum USU_MODEL height to use; km
119	600	Maximum USU_MODEL height to use; km
120	0.8	Horizontal control distance factor
121	0.8	Vertical control distance factor
122	0.6	Initial scale factor for a_i
123	6.0	Range of influence factor
124	0.0625	Iteration adjustment factor
125	0.1	Maximum error to terminate iterations
126	51	Maximum number of iterations

SAMPLE PROBLEM

A sample problem is presented here to illustrate the unification of the individual models. The path is defined in geographic coordinates from 40°N, 90°W to 80°N, 90°W. The geographic bearing angle is 0° and the path length is 4400 km. The ionospheric profiles are generated for 15 July 1991 at 1800 hours UT. The 10-cm flux is 200, the k_p is 5, and the direction of the sun's magnetic field, B_y, is positive. Contour plots of the logarithm of the electron density in vertical planes along geographic bearings of -5°, 0°, and 5° are shown in figure 1. Clearly, the ionosphere is changing in all three dimensions. In particular, we note a broad maximum near 2 Mm, followed by a constriction of the contour lines near 3.2 Mm. Figure 2 shows the resulting ray paths. The top panel (figure 2a) shows the projection of the ray paths onto the vertical plane passing through the transmitter and the receiver. The rays with small circles on their ends are rays that penetrate the ionosphere, and we see that this penetration occurs where we see a reduction in electron density in figure 1. The bottom panel of figure 2 (figure 2b) shows the projection of the ray paths onto the ground with locations above the horizontal axis being to the west of the propagation path. We see that the east-west variation of the ionosphere causes some deflection of the ray paths.

CONCLUSION AND RECOMMENDATIONS

The iteration process required to obtain the coefficients for the interpolation model requires excessive computer time, and the interpolation is quite slow. A faster method is highly desirable. The current interpolation model still requires too much manual adjustment to be routinely used. The ionospheric model needs to be changed to give more realistic electron densities in the lower altitudes. *This will be very important if the model is to properly account for absorption.* The ray trace model has some difficulty with the radical changes introduced by the ionospheric model, and refinement of some of its procedures will be necessary.
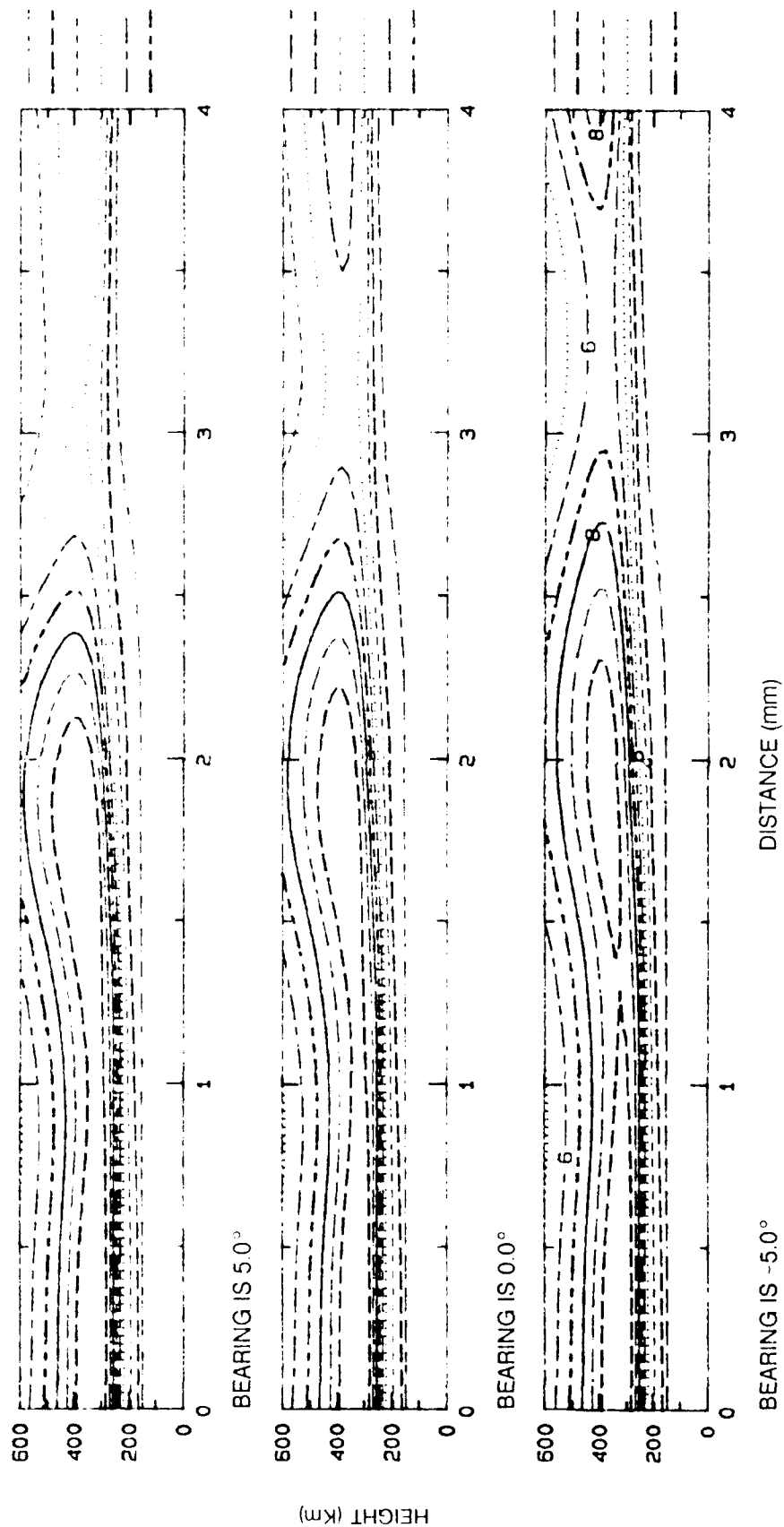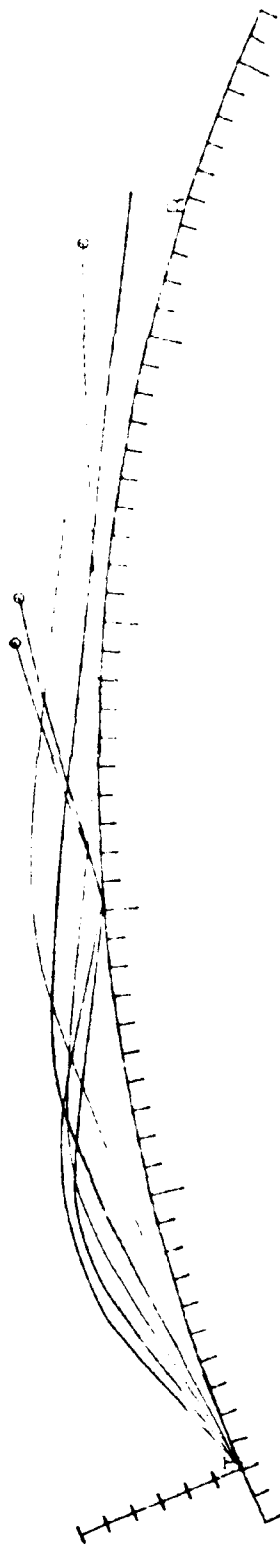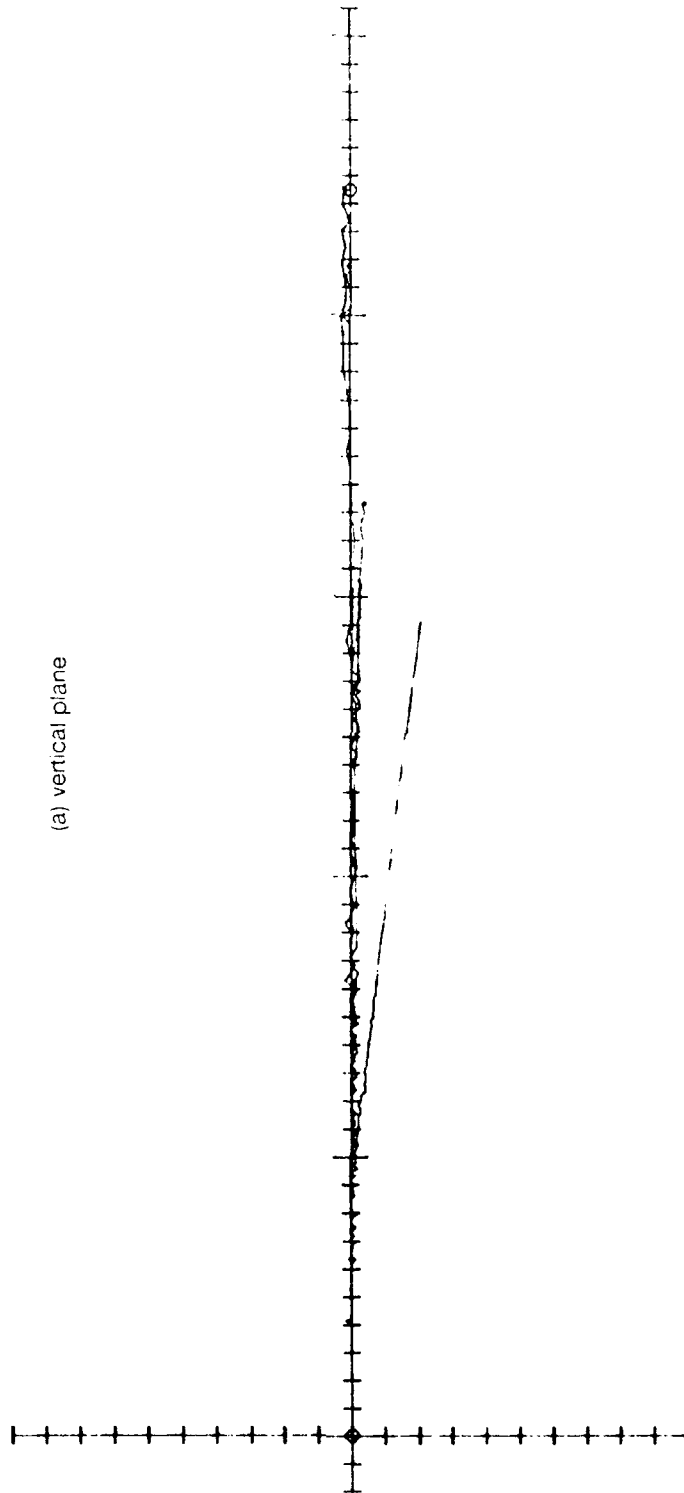
Figure 1. Plots of contours of constant values of the logarithm of the electron density in the vertical plane at bearing angles of –5°, 0°, and 5° with respect to the great circle path passing through the transmitter and receiver.

7

(a) vertical plane

(b) horizontal plane

Figure 2. Plots of the ray paths in the vertical plane passing through the transmitter and receiver (a) and in the horizontal plane (b).

8

REFERENCES

Jones, R. M., and J. J. Stephenson. 1975. "A Versatile Three-Dimensional Ray Tracing Computer Program for Radio Waves in the Ionosphere," U. S. Dept. of Commerce Office of Telecommunications Report, pp. 75-76.

Paul, A. K. 1985. "F-Region Tilts and Ionogram Analysis," *Radio Science.*, vol. 20, pp. 959-971.

Paul, A. K. 1991. "Fitting of Discrete Irregularly Spaced Discrete Data with Differentiable Functions: Application to Ray Tracing in the Ionosphere." NOSC TR 1405 (Mar). Naval Ocean Systems Center, San Diego, CA.

Sailors, D. B. 1990. "A review of the History of Field Strength Models Used in PROPHET." *Proceedings of the Ionospheric Effects Symposium.*

Teters, L. R., J. L. Lloyd, G. W. Haydon, D. L. Lucas. 1983. "Estimating the Performance of Telecommunications Systems Using the Ionospheric Transmission Channel." National Telecommunications and Information Agency Report, pp. 81-127.

APPENDIX A: COORDINATE TRANSFORMATIONS.

Coordinate conversion is needed because the ray trace program works in spherical coordinates and the interpolation routine uses Cartesian coordinates. A position, P, on a sphere defined by a colatitude, θ and longitude, ϕ must be converted to a distance, x, along a reference great circle path from the transmitter and a distance, y, perpendicular to that great circle. We chose this reference great circle to be the one which passes through both the transmitter and the receiver. The relevant geometry is shown in figure A-1. The transmitter position is labeled T and is located at colatitude θ_t and longitude ϕ_t. The great circle between the transmitter and the receiver (not shown) makes an angle, β, with respect to north. The position for which we need interpolation coordinates, x and y, is labeled P. In the figure, $\delta\phi$ is merely the difference in longitude between the transmitter and P. Note that the line segment, y, is perpendicular to the reference great circle.
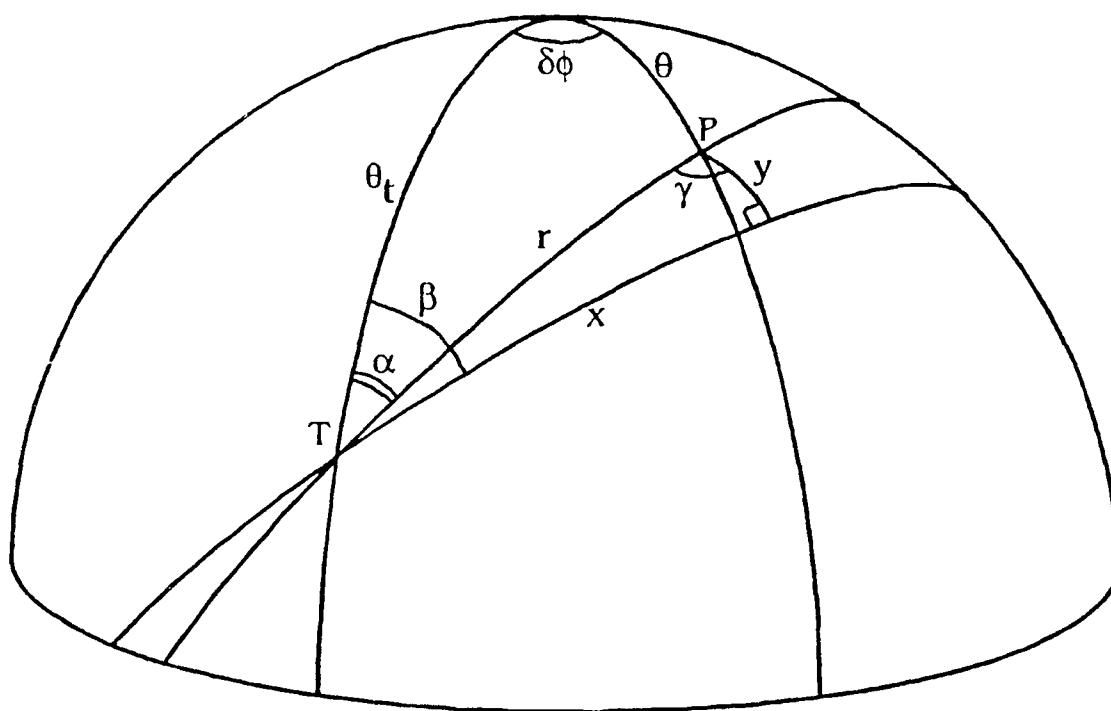

Figure A-1. Illustration of spherical coordinates to interpolation coordinates.

A-1

The law of cosines for sides gives the great circle distance, r, and the bearing angle, α, from the transmitter to P:

$$\cos r = \cos\theta \cos\theta_t + \sin\theta \sin\theta_t \cos\delta\phi$$

$$\cos\alpha = \frac{\cos\theta - \cos\theta_t \cos r}{\sin\theta_t \sin r}.$$

The law of sines gives

$$\sin\alpha = \frac{\sin\theta \sin\delta\phi}{\sin r}.$$

Referring to the right triangle defined by the sides labeled r, x, and y, the law of cosines for sides gives us

$$\cos x = \frac{\cos r}{\cos y}.$$

The law of sines gives

$$\sin y = \cos(\beta - \alpha)\cos y$$

and the law of cosines for angles gives us

$$\sin\gamma = \frac{\cos(\beta - \alpha)}{\cos y}.$$

Finally, the law of sines gives

$$\sin x = \sin\gamma \sin r.$$

These equations can be combined to eliminate α, r, and γ:

$$\sin y = \cos\theta \sin\theta_t \sin\beta - \sin\theta (\cos\beta \sin\delta\phi + \cos\theta_t \sin\beta \cos\delta\phi)$$

$$\sin x = \frac{\cos\theta \sin\theta_t \cos\beta + \sin\theta (\sin\beta \sin\delta\phi - \cos\theta_t \cos\beta \cos\delta\phi)}{\cos y}$$

$$\cos x = \frac{\cos\theta \cos\theta_t + \sin\theta \sin\theta_t \cos\delta\phi}{\cos y}.$$

The ray tracing routine also requires the derivatives of the ionospheric parameters with respect to the spatial dimensions. The necessary equations are listed below.

$$\frac{d \sin y}{d\theta} = -\sin\theta \, \sin\theta_t \, \sin\beta - \cos\theta \, (\cos\beta \, \sin\delta\phi + \cos\theta_t \, \sin\beta \, \cos\delta\phi)$$

$$\frac{d \sin y}{d\phi} = -\sin\theta \, (\cos\beta \, \cos\delta\phi - \cos\theta_t \, \sin\beta \, \sin\delta\phi)$$

$$\frac{\partial \sin x}{\partial\theta} = \frac{-\sin\theta \, \sin\theta_t \, \cos\beta + \cos\theta \, (\sin\beta \, \sin\delta\phi - \cos\theta_t \, \cos\beta \, \cos\delta\phi)}{\cos y}$$

$$\frac{\partial \sin x}{\partial\phi} = \frac{\sin\theta \, (\sin\beta \, \sin\delta\phi + \cos\theta_t \, \cos\beta \, \sin\delta\phi)}{\cos y}$$

$$\frac{\partial \cos x}{\partial\theta} = \frac{-\sin\theta \, \cos\theta_t + \cos\theta \, \sin\theta_t \, \cos\delta\phi}{\cos y}$$

$$\frac{\partial \cos x}{\partial\phi} = -\frac{\sin\theta \, \sin\theta_t \, \sin\delta\phi}{\cos y}$$

$$\frac{d \sin x}{d\theta} = \frac{\partial \sin x}{\partial\theta} + \frac{\sin x \, \sin y}{\cos^2 y} \frac{d \sin y}{d\theta}$$

$$\frac{d \sin x}{d\phi} = \frac{\partial \sin x}{\partial\phi} + \frac{\sin x \, \sin y}{\cos^2 y} \frac{d \sin y}{d\phi}$$

$$\frac{d \cos x}{d\theta} = \frac{\partial \cos x}{\partial\theta} + \frac{\cos x \, \sin y}{\cos^2 y} \frac{d \sin y}{d\theta}$$

$$\frac{d \cos x}{d\phi} = \frac{\partial \cos x}{\partial\phi} + \frac{\cos x \, \sin y}{\cos^2 y} \frac{d \sin y}{d\phi}$$

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE November 1991	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE SPATIAL SMOOTHING OF IONOSPHERIC PARAMETERS FOR USE IN THE HIGH-FREQUENCY BENCHMARK PROPAGATION ANALYSIS PROGRAM	5. FUNDING NUMBERS PE: 0602435N PROJ: SXB3 WU: DN888715
6. AUTHOR(S) J. A. Ferguson and C. H. Shellman	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Ocean Systems Center San Diego, CA 92152–5000	8. PERFORMING ORGANIZATION REPORT NUMBER NOSC TR 1469

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Technololgy Arlington, VA 22217	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes a computer program for the spatial smoothing of ionospheric parameters for use in the High-Frequency (HF) Benchmark Propagation Analysis Program. The HF Benchmark, being developed at the Naval Ocean Systems Center (NOSC), employs a sophisticated ray tracing program coupled with a state-of-the-art ionospheric model. The merging of these two major components depends critically on the development of a spatial smoothing routine that accepts arbitrary ionospheric models as input.

14. SUBJECT TERMS		15. NUMBER OF PAGES
high-frequency propagation modeling spatial smoothing ionospheric model propagation analysis ray tracing		20
		16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE *(include Area Code)*	21c. OFFICE SYMBOL
J. A. Ferguson	(619) 553–3062	Code 542